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TECHNICAL NOTE

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PRELIMINARY EXPERIMENTAL INVESTIGATION OF FREQUENCIES AND FORCES RESULTING FROM LIQUID SLOSHING IN TOROIDAL TANKS

By Irving E. Sumner

Lewis Research Center
Cleveland, Ohio

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PRELIMINARY EXPERIMENTAL INVESTIGATION OF FREQUENCIES AND FORCES RESULTING FROM LIQUID SLOSHING IN TOROIDAL TANKS

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SUMMARY

A preliminary experimental investigation was conducted to determine the natural mode frequencies and slosh forces resulting from liquid oscillation in three horizontally oriented toroidal tanks of constant minor radius and varied major radii. The excitation amplitude was held constant, and the excitation frequency was varied to encompass the first and second natural modes of the contained liquids over a range of liquid-depth ratios.

The slosh forces were found to be directly proportional to the density of the contained liquid for liquids of about the same viscosity.

As the major radius of the tank was increased, the maximum first mode slosh forces increased and were found to occur at progressively higher liquid-depth ratios. There was not a consistent trend of first mode slosh forces with the tank major radius at a constant liquid-depth ratio. The maximum second mode slosh forces increased and became significantly greater than those of the first mode as the major radius was increased. The maximum second mode slosh forces always occurred at a liquid-depth ratio of 0.5.

INTRODUCTION

For space vehicles that contain relatively large masses of liquid propellants, sloshing is a potential source of disturbance critical to the stability of the vehicle. For example, oscillations of the propellant masses may result from attitude stabilization control pulses and can exert forces and moments that may have an adverse effect on the stability and structural integrity of the vehicle. The most critical situation occurs when the excitation frequency becomes very nearly the same value as one of the natural frequencies of the contained liquid, which causes a coupling action between the attitude control pulses and the slosh forces.

The natural frequencies and, to a lesser extent, the forces produced by liquid sloshing have been investigated both analytically and experimentally for several different tank configurations (e.g., refs. 1 to 8). In many recent design studies of lunar space vehicles, toroidal propellant tanks have been proposed because of packaging considerations. None of the information presently available, however, is related to liquid sloshing in toroidal tanks with the exception of reference 3. In that report an experimentally verified empirical method of predicting the first four natural frequencies of the liquid oscillations is presented.

Accordingly, a preliminary experimental investigation of liquid sloshing in three horizontally oriented toroidal tank configurations was conducted at the Lewis Research Center to determine the resulting slosh forces and the natural slosh frequencies over a range of liquid-depth ratios. For these tank configurations, the minor radius was held constant, and the major radius was varied. The excitation amplitude was held constant, and the excitation frequency was varied to encompass the first and second natural modes of the contained liquid. Tap water, mercury, and acetylene tetrabromide were employed as the contained slosh liquids. The results of this preliminary investigation are presented in terms of the slosh force as a function of the excitation frequency and liquid-depth ratio for each tank configuration.

SYMBOLS

F_s	horizontal slosh force, lb
f	excitation frequency, cps
h	liquid depth, in.
R	toroidal tank major radius, in.
r	toroidal tank minor radius, in.
s.g.	specific gravity of contained liquid
X_o	excitation amplitude, in.
δ	damping ratio, or logarithmic decrement, $\ln(F_{s,n}/F_{s,n+1})$
μ	liquid viscosity, centipoises

Subscript:

n	cycle number $(n = 0,1,2, \ldots, n)$

APPARATUS AND INSTRUMENTATION

The experimental apparatus is shown in figure 1. The test facility is nearly identical to that used in the investigation of unrestricted sloshing in spherical tanks, as reported in reference 4. Three toroidal tanks were formed in laminated lucite blocks. When placed on the test facility, each tank was mounted on ball bearings and was free to oscillate in a horizontal plane. The sinusoidal motion of the tank was produced by a slider-crank mechanism driven through a variable speed transmission by an alternating current electric motor. The excitation amplitude of the tank was held constant at 0.050 inch, and the excitation frequency could be varied from 0 to 5 cycles per second. The electric driving motor was wired so that the alternating current could be removed from the field and a direct current could be supplied to one of the windings. This enabled the oscillatory motion to be "quick-stopped" so that only the horizontal forces resulting from the liquid motion were measured. These residual slosh forces were sensed by a strain gage mounted between the tank and the slider-crank mechanism. The signal from the strain gage was recorded by means of a continuously recording strip chart.

Water and mercury were used as the initial contained liquids in order to cover a range of densities and slosh forces at the given excitation amplitude. These two liquids were chosen because of their wide range of densities and nearly equal values of absolute viscosity (approx. 1 centipoise). Acetylene tetrabromide (TBE) was also used as the contained liquid to determine the maximum first and second mode slosh forces over the range of liquid-depth ratios. TBE was used for this portion of the investigation because (1) its density (2.97 times that of water) was high enough to provide a relatively accurate measurement of the slosh forces and (2) the absolute viscosity (9.7 centipoises) was high enough to provide sufficient damping so that the maximum wave height of the liquid did not occur until the tank had completed at least one cycle of its oscillatory motion. Table I summarizes the tank configurations and contained liquids used in this investigation.

PROCEDURE

The tank and the contained liquid were oscillated at a preset amplitude (X_o = 0.050 in.) and a preselected frequency until the maximum wave height was obtained; then the oscillatory motion was quick-stopped, and the residual slosh forces were recorded. Initial tests with water, mercury, and TBE were conducted at a liquid-depth ratio $h/2r$ of 0.50. Later tests conducted with TBE covered a range of liquid-depth ratios from 0.1 to 0.95.

DATA REDUCTION

Oscillograph traces of the slosh forces typical of those obtained for any tank configuration and liquid-depth ratio are shown in figure 2. The large forces to the left of time zero were those recorded while the tank was being driven through the oscillatory motion. At time zero, this oscillatory motion was quick-stopped; after time zero, only the forces resulting from the motion of the liquid contained within the tank were recorded. The slosh force measurements were obtained from the first force peak that occurred immediately after the oscillatory motion of the tank had been quick-stopped. The damping ratios were calculated as the logarithmic decrement of a smooth curve faired through successive force peaks.

RESULTS AND DISCUSSION

The liquid-surface forms of the contained liquid, when the tank was oscillated at excitation frequencies at or near that of the first and second natural modes, are shown in figure 3. At or near the first mode frequency, the entire liquid surface oscillates as a plane that pivots about a horizontal centerline normal to the direction of excitation. At or near the second mode frequency, the liquid may be considered to be divided into three distinct sections. The liquid surface in each section (1 and 3) oscillates as a plane that pivots about a section horizontal centerline normal to the direction of excitation. The surface of the liquid in section 2 assumes a form to provide continuity between the surfaces in sections 1 and 3.

The first two natural frequencies of oscillation of the contained liquid were calculated over a range of liquid-depth ratios by the method presented in reference 3. Experimental values of the first and second natural frequencies of liquid oscillations were determined from the oscillograph traces and are compared with the calculated values in figure 4. Agreement between the calculated and experimental values is good, particularly for liquid-depth ratios in the range of 0.4 to 0.7. In general, a decrease in the liquid-depth ratio results in a decrease of both the first and second natural frequencies of liquid oscillation. For a constant minor radius, an increase in the major radius of the tank also results in a decrease of both the first and second natural frequencies. The density and viscosity of the contained liquid had no effect on the natural frequency of oscillation in this investigation. The wave forms of higher modes could not be obtained because the ratio of the excitation amplitude to tank minor radius X_o/r was too large to establish the characteristic wave form.

Slosh forces obtained in toroidal tank configuration A (major radius, R = 3.75 in.) for excitation frequencies encompassing the first fundamental mode are presented in figure 5(a). The slosh forces increased to a peak value as the excitation frequency approached the first fundamental mode frequency and then decreased with a further increase of the excitation frequency. The slosh forces are presented in the form of a specific slosh force (the ratio of the measured slosh force to the specific gravity of the contained liquid, F_s/s.g.) in order to generalize the effect of liquid density. For water and mercury, the slosh forces were found to be directly proportional to liquid density; however, the maximum specific slosh forces for TBE were lower than those obtained for water or mercury because of its higher absolute viscosity. Unpublished data from an investigation conducted with several glycerine-water mixtures sloshed in a spherical tank indicate that an increase of the viscosity of the contained liquid will decrease the slosh force, particularly for slosh forces obtained at or near a natural frequency. This decrease of the slosh forces may be expected to occur to a greater extent in a toroidal tank because the volume to surface-area ratio is lower than that of a spherical tank.

Slosh forces obtained in toroidal tank configuration A, for excitation frequencies encompasing the second natural mode, are presented in figure 5(b) The slosh forces obtained at the second mode frequency were about the same magnitude as the slosh forces obtained at the first mode and represented approximately 5 percent of the apparent weight of the contained liquid.

Slosh forces from the three toroidal tank configurations are compared in figure 6. Specific slosh forces are presented for excitation frequencies extending through the first two modes of the contained liquid (water or mercury) at a liquid-depth ratio of 0.50. The natural frequencies of the first and second modes decreased with an increase in the major radius R, as previously shown in figure 4. As the toroidal tank major radius was increased (1) the first fundamental mode slosh forces decreased, (2) the second mode slosh forces increased, and (3) the second mode slosh forces became significantly greater than the forces that occurred at the first mode.

The variation of the first and second mode specific slosh forces with liquid-depth ratio for TBE as the contained liquid is presented in figure 7. Each toroidal tank configuration was oscillated at the specific first and second mode excitation frequency dictated by the depth ratio of the contained liquid and the specific tank geometry (fig. 4). For tank configuration A, the first mode specific slosh force reached a maximum value of approximately 0.45 at a liquid-depth ratio of 0.5. As the major radius of the tank was increased, the maximum values of the first mode slosh forces increased and occurred at higher liquid-depth ratios. There was not a consistent trend of the first mode slosh forces with tank major radius at a constant liquid-depth ratio. The second mode specific slosh forces for each tank configuration reached a maximum value at a liquid-depth ratio of 0.50, and the curves tended to be symmetrical about that depth ratio. The maximum second mode slosh forces increased as the major radius increased and were still significantly greater than the maximum first mode slosh forces. The maximum first and second mode slosh forces and the liquid-depth ratio at which each occurred are summarized in the following table:

Tank configuration	Tank major radius, R, in.	First mode		Second mode	
		Maximum specific slosh force, F_s/s.g., lb	Liquid-depth ratio, h/2r	Maximum specific slosh force, F_s/s.g., lb	Liquid-depth ratio, h/2r
A	3.75	0.45	0.5	0.45	0.5
B	6.25	.76	.7	1.16	.5
C	8.75	.81	.8	1.70	.5

The maximum second mode slosh forces varied in magnitude from 5.4 percent of the apparent weight of the contained liquid for tank configuration A to 8.7 percent for configuration C.

The difference in specific slosh force levels that appears at any given value of excitation frequency or liquid-depth ratio (figs. 5 to 7) is attributed to experimental technique. As each tank was oscillated, the wave forms were allowed to build to a maximum height (determined visually) without breaking up and showering liquid throughout the tank; then the tank was quick-stopped. The maximum slosh forces occurred just before the waves broke. At excitation frequencies near the first fundamental frequency, the waves would build up very slowly; near the second natural frequency, the waves would build up very rapidly. The data scatter is attributed to the difficulty in quick-stopping the tank at precisely the proper time.

Damping ratios determined from the first and second mode slosh force oscillograph traces are presented as a function of liquid-depth ratio in figure 8. The contained slosh liquid was TBE. The damping ratios tended (1) to be independent of the toroidal tank configuration and (2) to decrease to a minimum value at the liquid-depth ratio where the specific slosh forces had reached a maximum value (fig. 7).

Liquid swirl, a rotation of the contained liquid in a tank resulting from the degeneration of linear, or conventional, slosh, previously has been reported to occur in cylindrical and spherical tanks (e.g., ref. 4). Liquid swirl was also noted in toroidal tanks at excitation frequencies very near those of the fundamental mode frequency when the contained slosh liquid was either water or mercury. Liquid swirl was not observed when TBE was used; the higher viscosity of TBE apparently damped any liquid rotation.

A dimensional analysis was conducted in an attempt to determine dimensionless slosh force and frequency parameters that would generalize the experimental data in terms of tank geometry. However, primarily because of the behavior of the first mode slosh forces when related to tank geometry and liquid-depth ratio, force and frequency parameters that would adequately describe the experimental data could not be determined from a dimensional analysis.

CONCLUDING REMARKS

A preliminary experimental investigation was conducted to determine the natural mode frequencies and slosh forces resulting from liquid oscillations in three horizontally oriented toroidal tanks. The tank configurations had a constant minor radius but different values of the major radius.

The first and second mode natural frequencies decreased with (1) a decrease in the depth ratio $h/2r$ of the contained liquid and (2) an increase in the major radius R of the tank. The experimental fundamental frequencies determined for a given toroidal tank configuration were found to be in good agreement with those values calculated by the method presented in reference 3.

The slosh forces increased to peak values as the excitation frequency approached the first or second natural mode frequencies and then decreased with a further increase of the excitation frequency. There was not a consistent trend of the first mode slosh forces with the tank major radius at a constant liquid-depth ratio. The maximum first mode slosh forces increased with an increase of the tank major radius (within the range investigated) and occurred at progressively higher liquid-depth ratios. The maximum second mode slosh forces increased and became significantly greater than those of the first mode as the major radius was increased. The maximum second mode slosh forces always occurred at a liquid-depth ratio of 0.50 and varied between 5.4 and 8.7 percent of the apparent weight of the contained liquid (acetylene tetrabromide).

The slosh forces were directly proportional to the liquid density for liquids of the same absolute viscosity.

Damping ratios associated with the first and second mode slosh forces were of approximately the same values, were independent of the tank configuration, and tended to reach a minimum value at the liquid-depth ratios where the slosh forces had reached a maximum value.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, February 5, 1963

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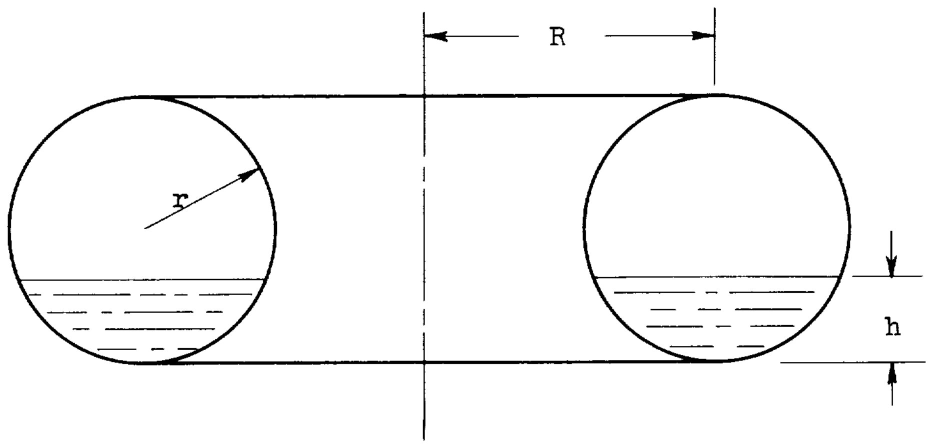
TABLE I. - SUMMARY OF TANK CONFIGURATIONS AND CONTAINED LIQUIDS



Tank configuration	Minor radius, r, in.	Major radius, R, in.
A	2.50	3.75
B	2.50	6.25
C	2.50	8.75

Contained slosh liquid	Specific gravity, s.g.	Absolute viscosity, μ, centipoises
Water	1.0	1.0
Mercury	13.55	1.5
Acetylene tetrabromide	2.97	9.7

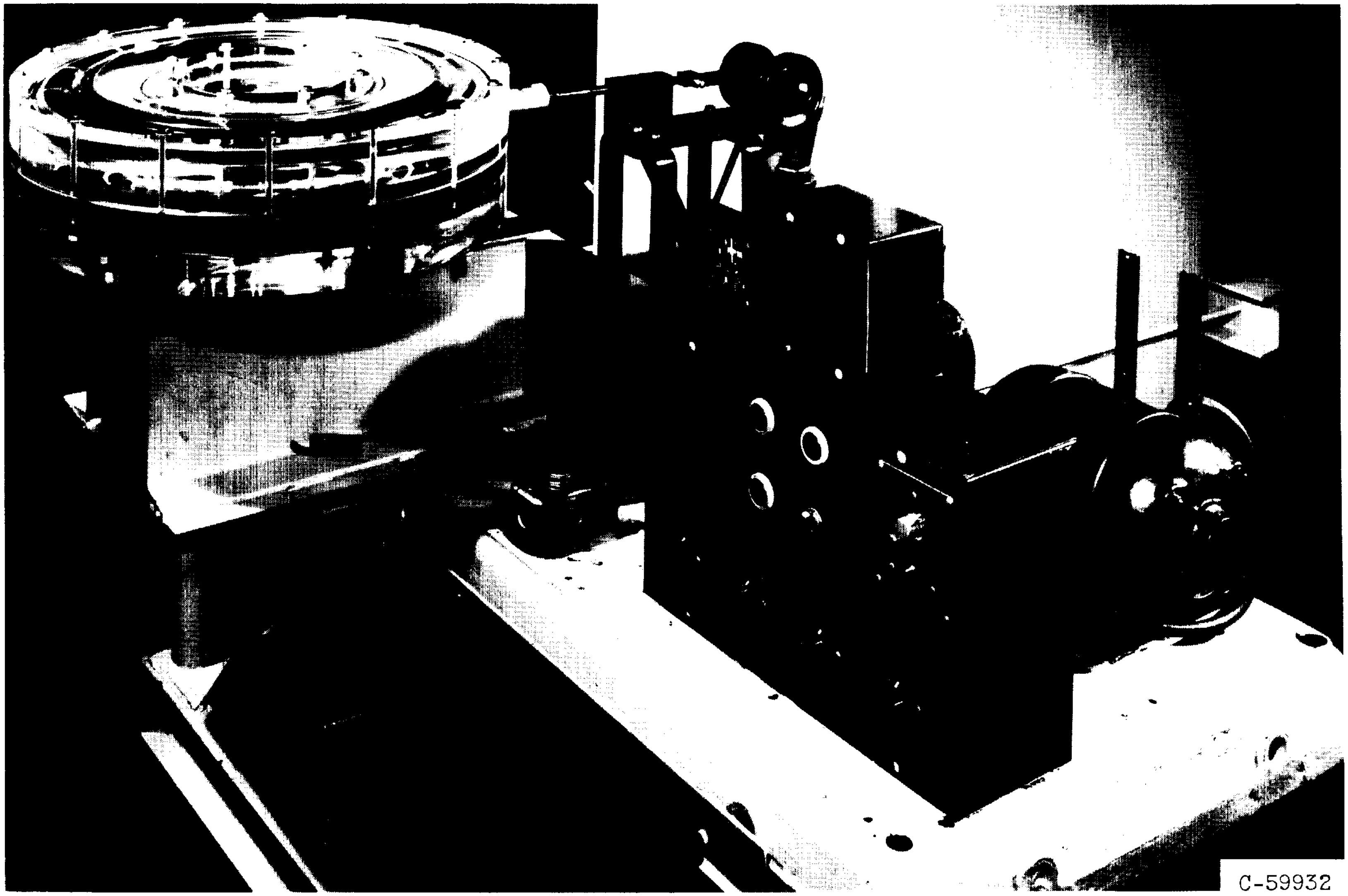


Figure 1. - Experimental toroidal tank slosh force test facility.

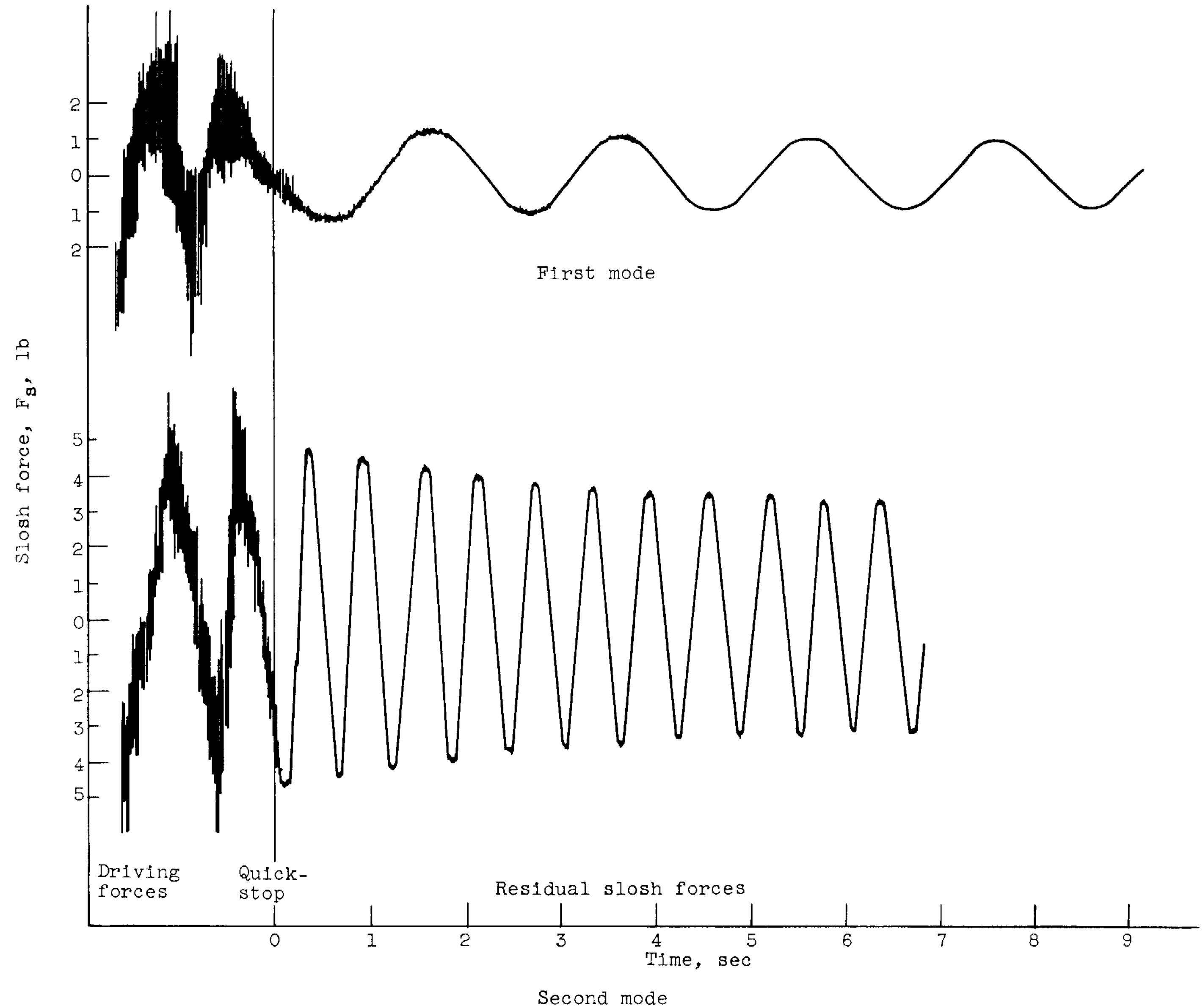
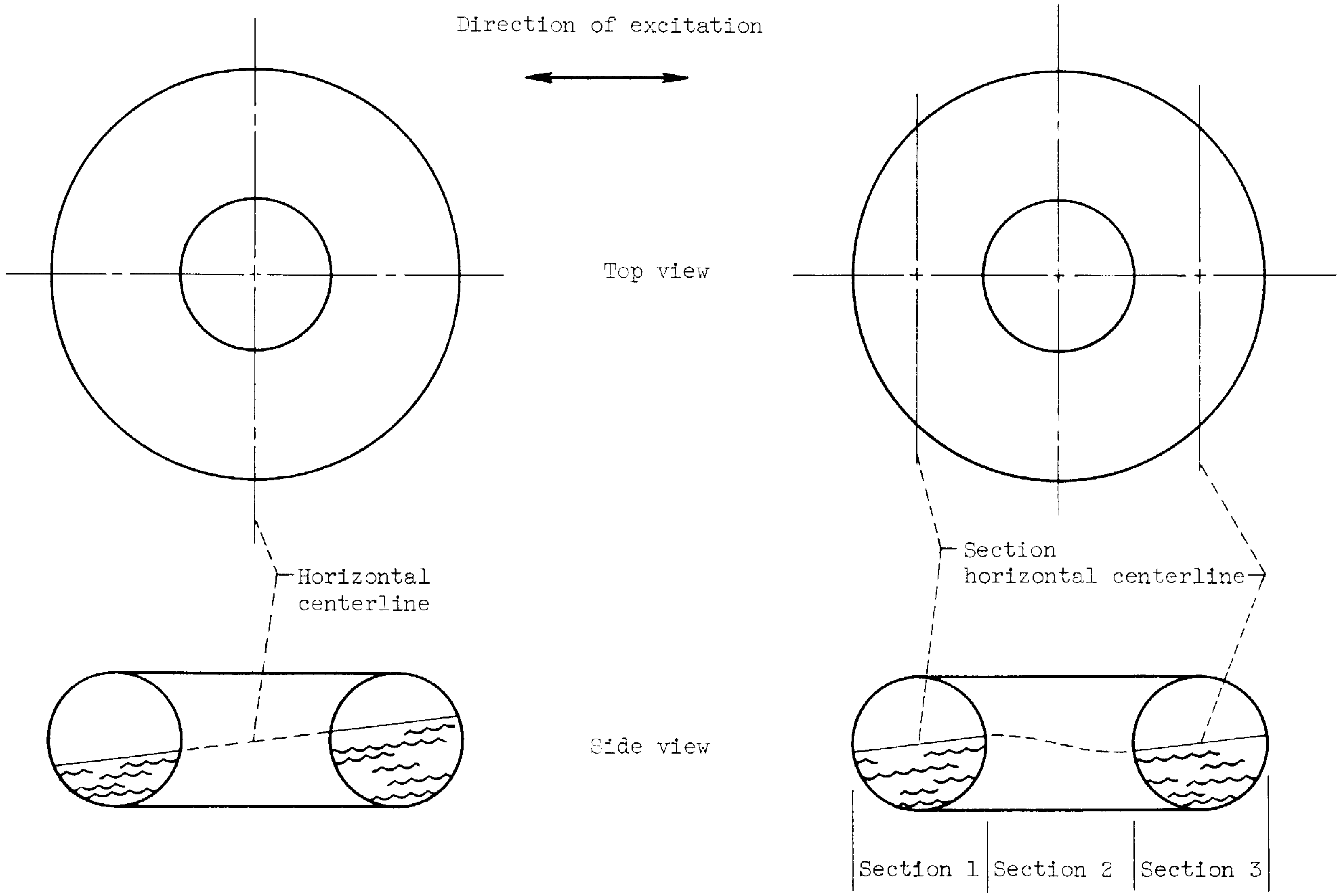


Figure 2. - Typical slosh-force - time oscillograph traces. Contained slosh liquid; acetylene tetrabromide; toroidal tank major radius, 8.75 inches; liquid-depth ratio, 0.05; excitation amplitude, 0.050 inch.



Liquid-surface form for excitation frequency at or near first natural mode

Liquid-surface form for excitation frequency at or near second natural mode

Figure 3. - Liquid-surface forms for the first and second natural modes.

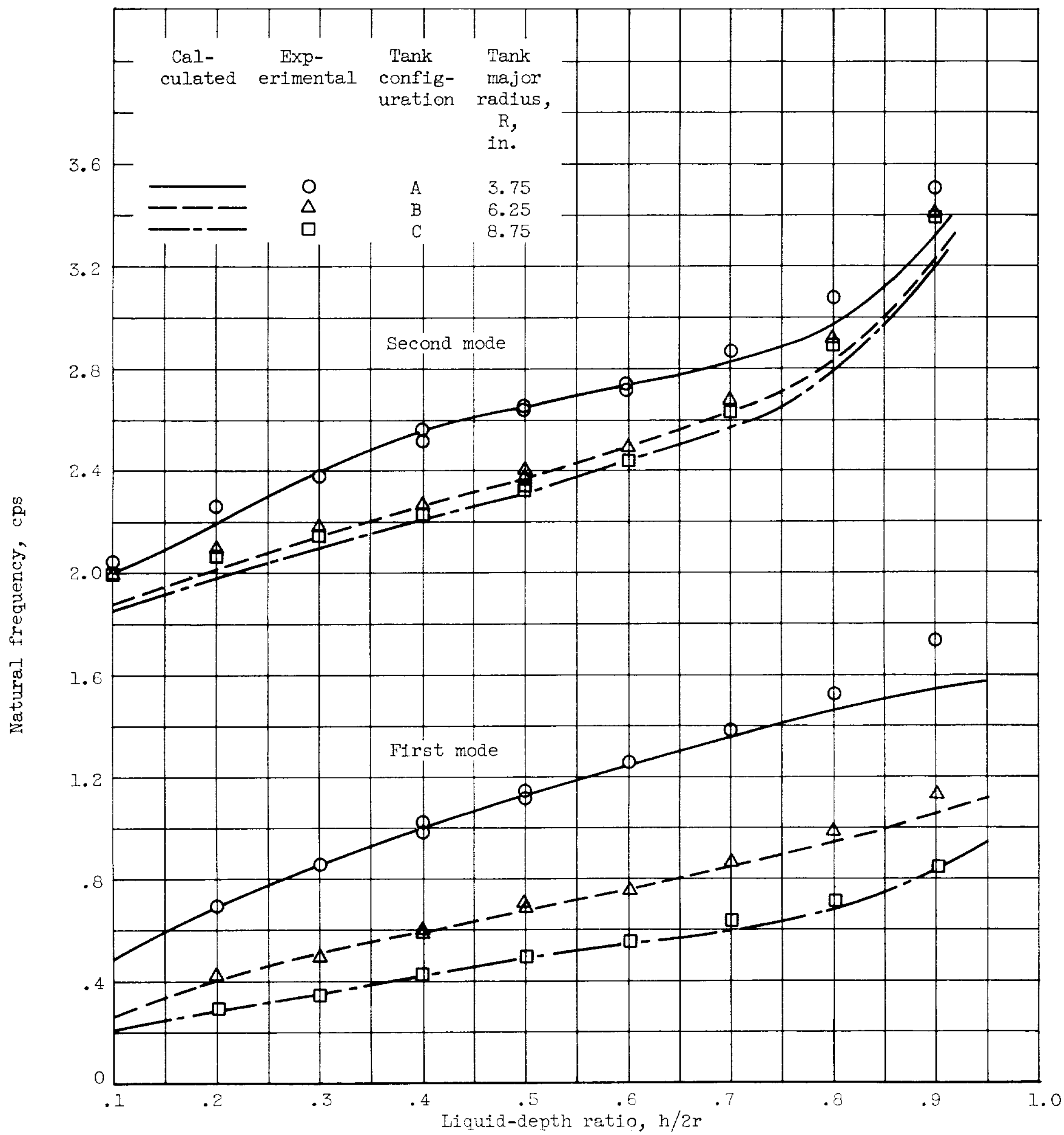
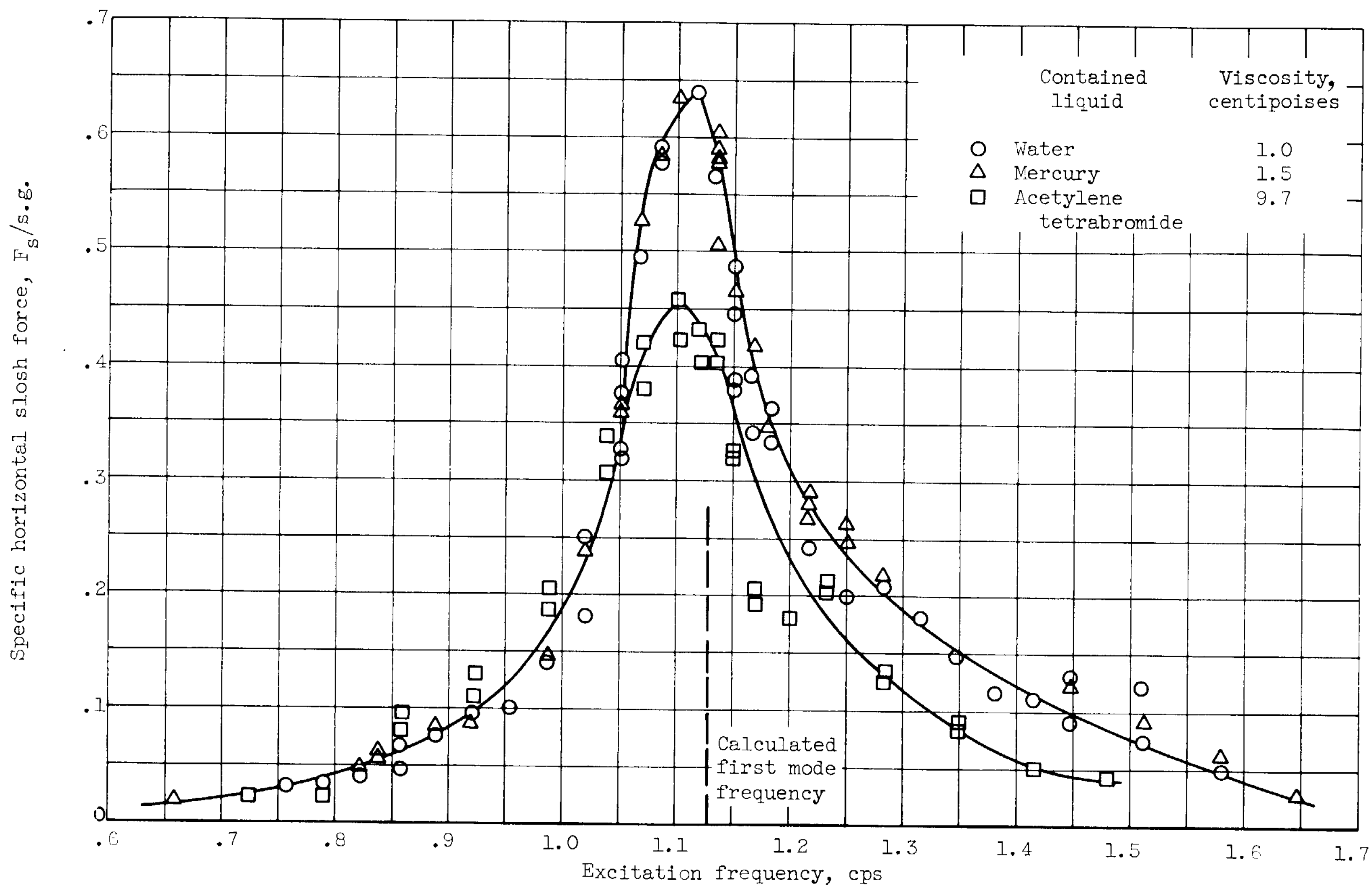
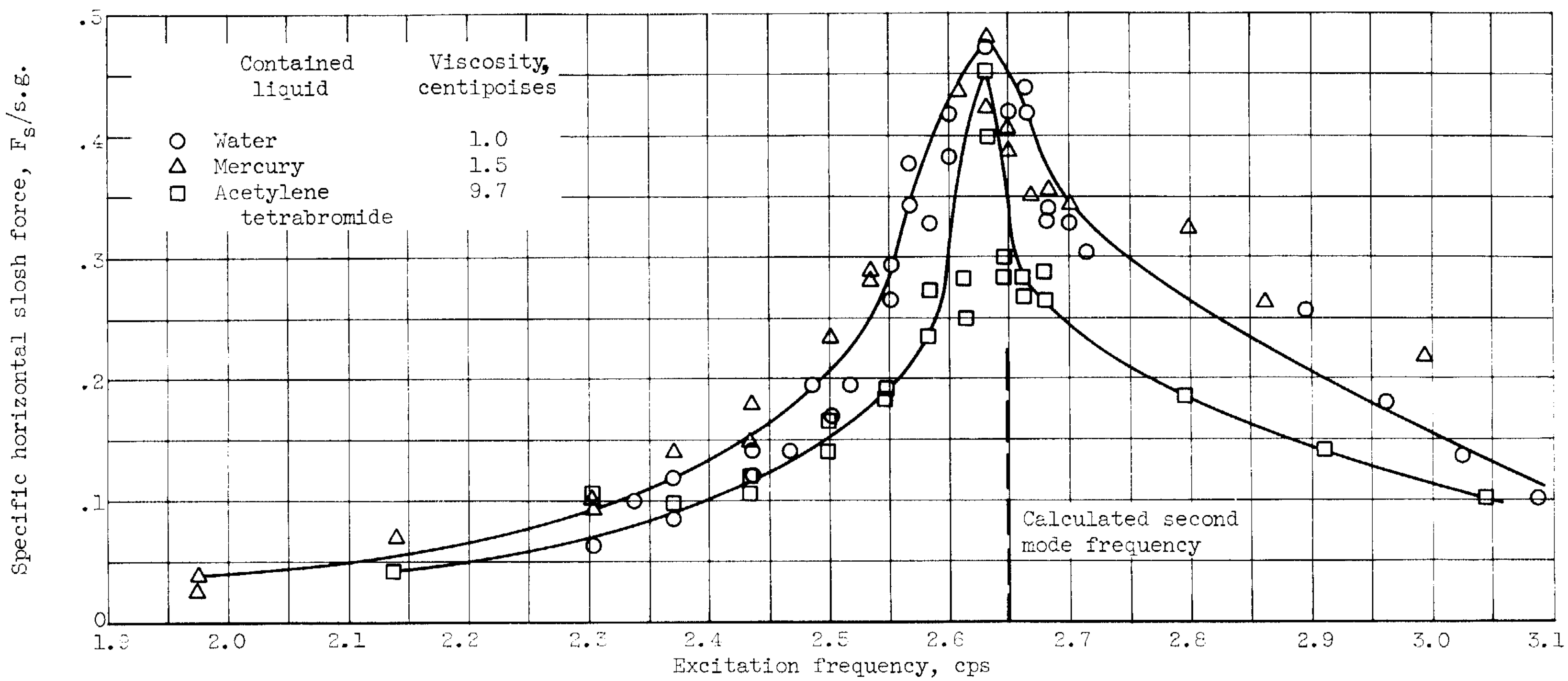


Figure 4. - Calculated and experimental values of the natural frequencies of the first two modes.



(a) First mode.

Figure 5. - Slosh forces for toroidal tank configuration A (tank major radius, 3.75 in.) at a liquid-depth ratio of 0.50.



(b) Second mode.

Figure 5. - Concluded. Slosh forces for toroidal tank configuration A (tank major radius, 3.75 in.) at a liquid depth ratio of 0.50.

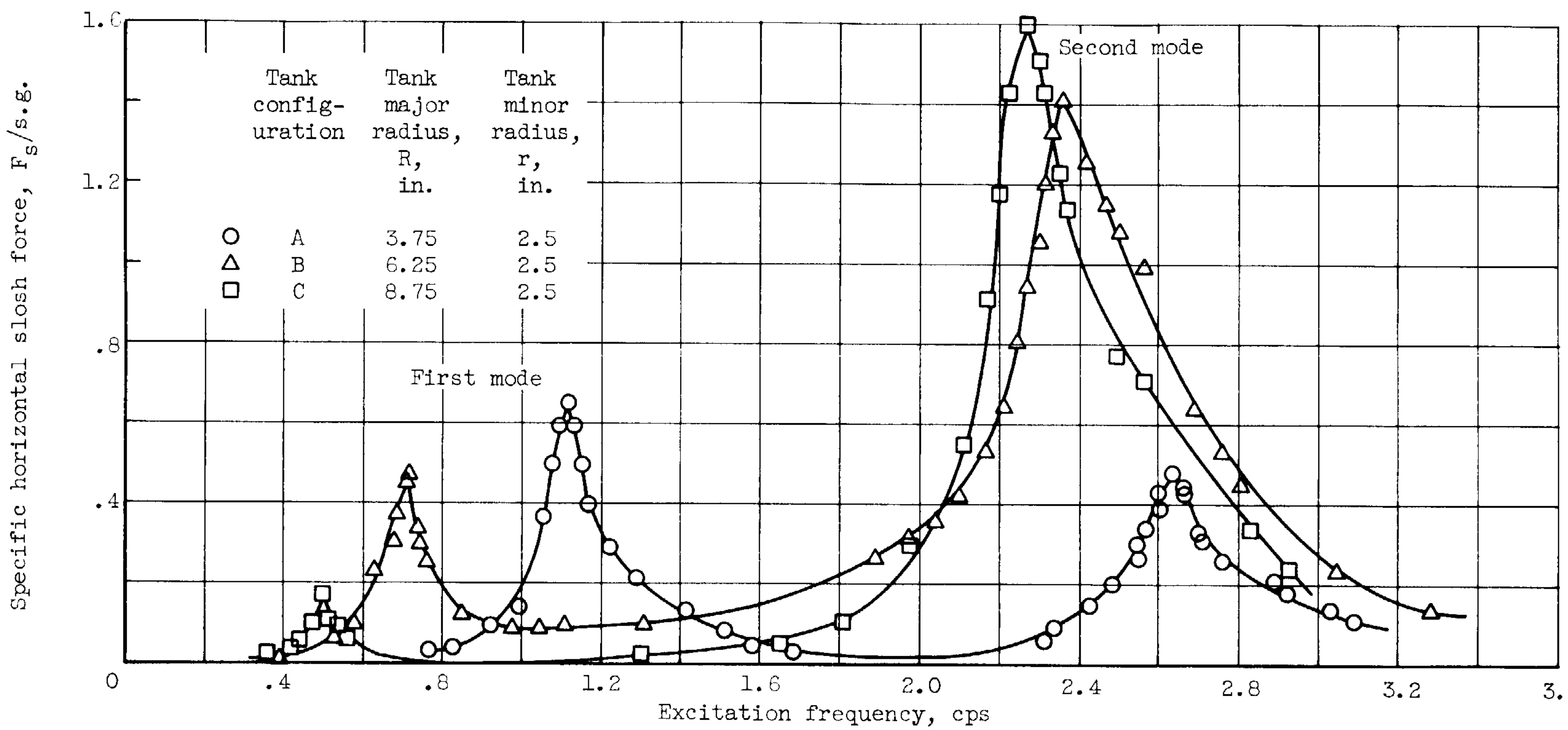
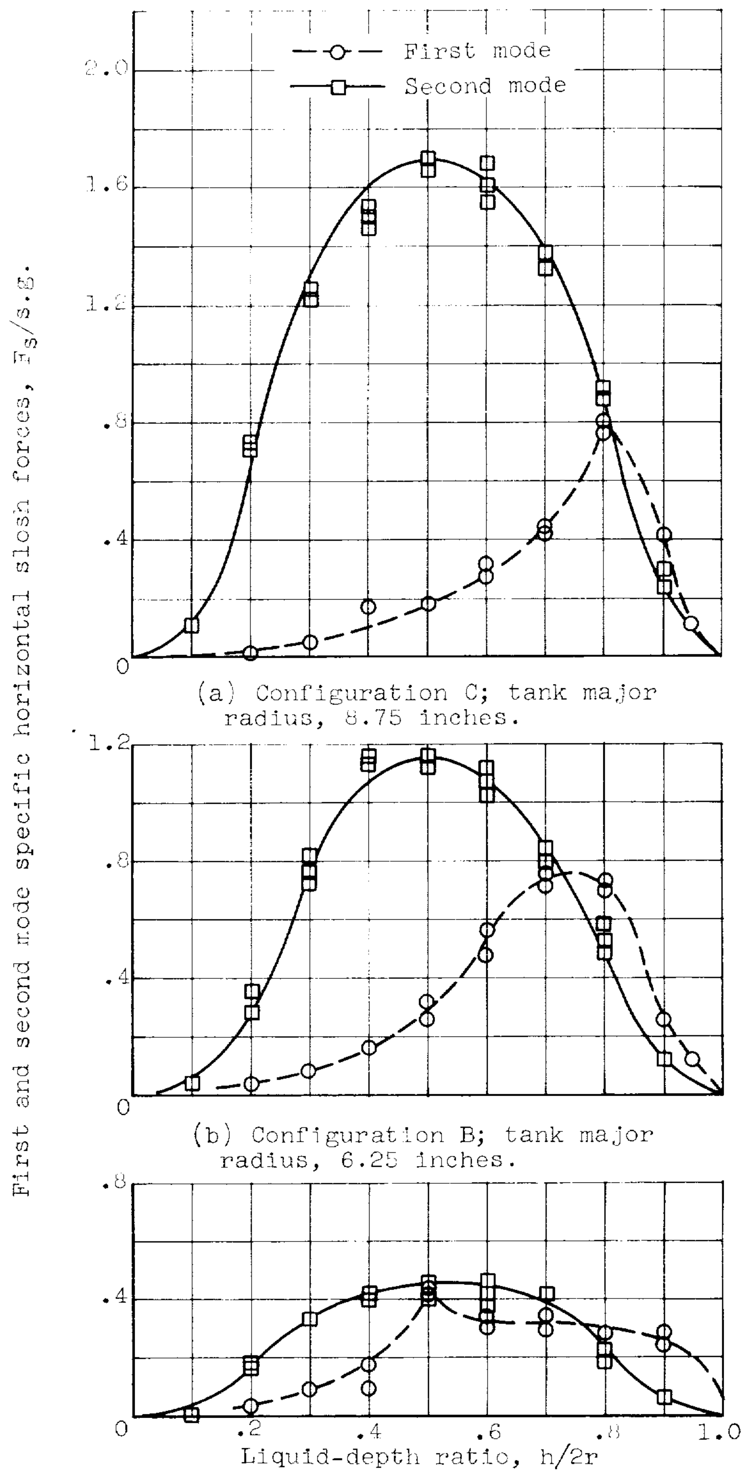


Figure 6. - First and second mode slosh forces for water and mercury at a liquid-depth ratio of 0.50.

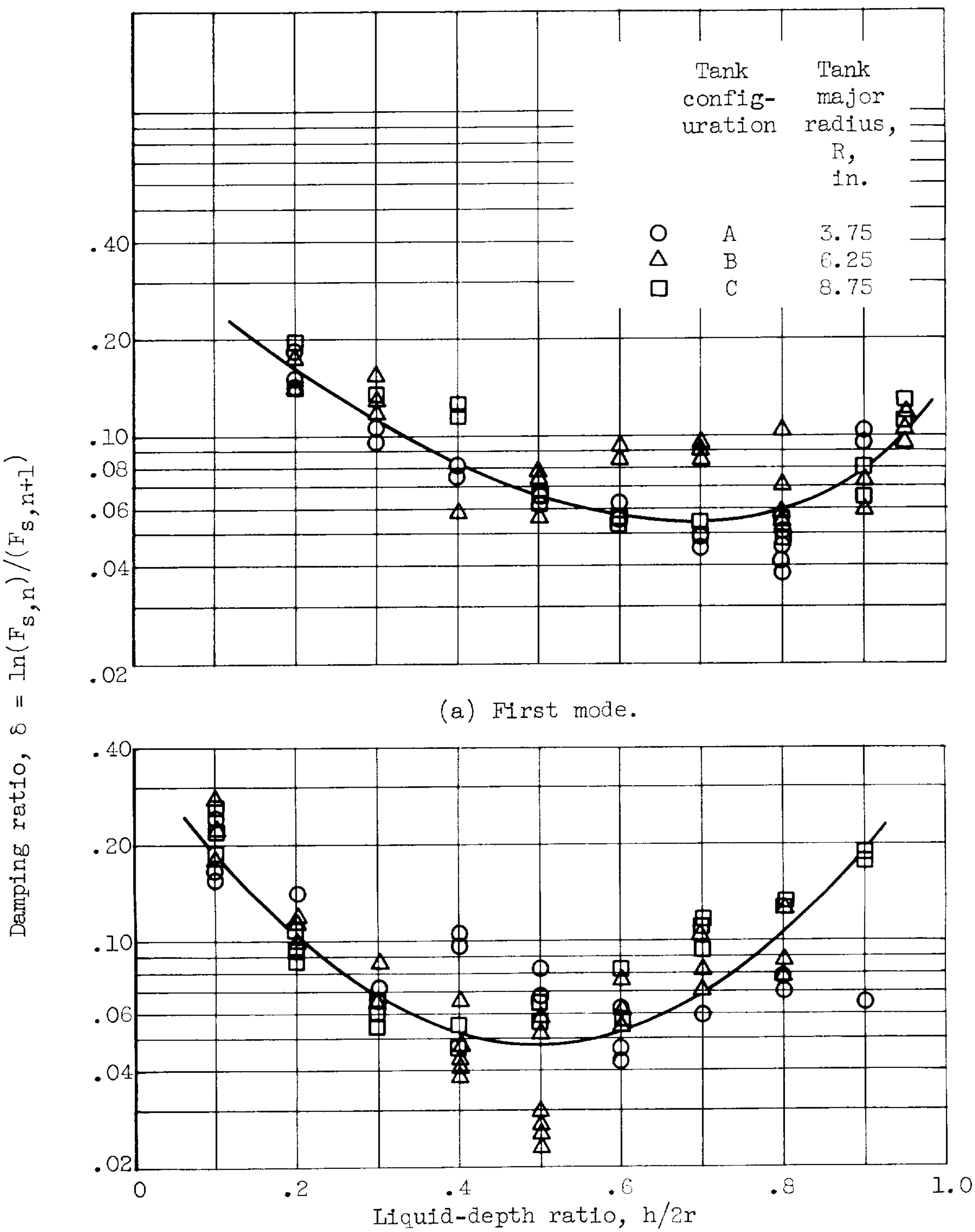


(a) Configuration C; tank major radius, 8.75 inches.

(b) Configuration B; tank major radius, 6.25 inches.

(c) Configuration A; tank major radius, 3.75 inches.

Figure 7. - Effect of liquid-depth ratio on maximum first and second mode slosh forces for acetylene tetrabromide.



(a) First mode.

(b) Second mode.

Figure 8. - Effect of liquid-depth ratio on the damping ratio for acetylene tetrabromide.